

Relic Gravity Waves and 7 keV Dark Matter from a GeV scale inflaton

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Abstract

We study the mechanism of generation of 7 keV sterile neutrino Dark Matter (DM) in the model with light inflaton χ , which serves as a messenger of scale invariance breaking. In this model the inflaton, in addition to providing reheating to the Standard Model (SM) particles, decays directly into sterile neutrinos. The latter are responsible for the active neutrino oscillations via seesaw type I like formula. While the two sterile neutrinos may also produce the lepton asymmetry in the primordial plasma and hence explain the baryon asymmetry of the Universe, the third one being the lightest may be of 7 keV and serve as DM. For this mechanism to work, the mass of the inflaton is bound to be light ($0.1 - 1$ GeV) and uniquely determines its properties, which allows to test the model. For particle physics experiments these are: inflaton lifetime ($10^{-5} - 10^{-12}$ s), partial decay width of B-meson to kaon and inflaton ($10^{-6} - 10^{-4}$) and inflaton branching ratios into light SM particles like it would be for the SM Higgs boson of the same mass. For cosmological experiments these are: spectral index of scalar perturbations ($n_s \simeq 0.957 - 0.967$), and amount of tensor perturbations produced at inflation (tensor-to-scalar ratio $r \simeq 0.15 - 0.005$).

1. Introduction

Discovery of the neutral scalar with properties very close to what we expect for the SM Higgs boson [1, 2] and absence of any definite hints of supersymmetry at LHC asks for its replacement as a solution to gauge hierarchy problem. Some hope is associated with conformal or scale invariance that might be a symmetry of the SM at tree level, but for the only dimensionful parameter of the SM v which gives the vacuum expectation value to the Englert–Brout–Higgs (EBH) field. Yet this parameter may be generated by the vacuum expectation value of a new scalar field (scale invariance breaking messenger) introduced into particle physics, so that the SM sector is scale invariant at tree level.

The field itself may be used to solve other SM problems. Here we discuss the idea that it may serve as an inflaton in the early Universe. The renormalizable model realizing this idea was suggested in [3] and further developed in [4–6]. With only one dimensionful parameter explicitly breaking scale invariance in the inflaton sector, the model is consistent with cosmological observations [6] and constraints from particle physics related to the possible manifestation of the light inflaton in B-meson decays [5].

The model may be further extended by introducing three Majorana fermions N_I , $I = 1, 2, 3$, which are singlets with respect to the SM gauge group. Yukawa-type

coupling to inflaton provides these fermions with Majorana mass terms when the inflaton field obtains vacuum expectation value. The Yukawa-type couplings between N_I , EBH doublet, and SM lepton doublets lead to Dirac masses for neutrinos, and the active neutrino masses are then obtained from seesaw type I formula [7]. Hence the fermions serve as sterile neutrinos, and the Yukawa couplings in a part of the parameter space may explain the baryon asymmetry of the Universe via leptogenesis, e.g. implementing the ν MSM scheme [8, 9]. Remarkably, the lightest sterile neutrino N_1 , provided tiny coupling to active neutrinos, may serve as non-thermal DM produced by inflaton decays in the early Universe [3]. Therefore the suggested model with seven new degrees of freedom added to the SM explains the neutrino oscillations, DM phenomena, baryon asymmetry of the Universe and exhibits the inflationary dynamics at early times thus solving the Hot Big Bang theory problems.

Given the allowed range of the inflaton mass the DM sterile neutrino is naturally light here, $1 \text{ keV} < M_1 < 1 \text{ MeV}$. In this *Letter* we discuss the particular choice of $M_1 = 7 \text{ keV}$ motivated by recently found anomalous line in cosmic X-ray spectra of galaxy clusters and Andromeda galaxy observed by orbital telescopes [10, 11]. We outline the viable region of the model parameter space consistent with this choice of sterile neutrino mass and give definite predictions for the inflationary cosmological parameters and the inflaton mass, its lifetime and branching ratio of B-meson to inflaton which *allow to thoroughly investigate*

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this model. Remarkably, recent results of BICEP2 experiment [12] on detection of B-mode polarization, interpreted as primordial tensor perturbations, can completely fix all the parameters of the model.

The action of the light inflaton model augmented with three sterile neutrinos is [5, 6]

$$S_{XSM} = \int \sqrt{-g} d^4x (\mathcal{L}_{SM} + \mathcal{L}_{XH} + \mathcal{L}_N + \mathcal{L}_{\text{grav}}),$$

$$\mathcal{L}_{XH} = \frac{(\partial_\mu X)^2}{2} + \frac{m_X^2 X^2}{2} - \frac{\beta X^4}{4} - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2, \quad (1)$$

$$\mathcal{L}_{\text{grav}} = - \frac{M_P^2 + \xi X^2}{2} R, \quad (2)$$

$$\mathcal{L}_N = i \bar{N}_I \not{\partial} N_I - \left(F_{\alpha I} \bar{L}_\alpha N_I \tilde{H} + \frac{f_I}{2} \bar{N}_I^c N_I X + \text{h.c.} \right), \quad (3)$$

where R is the scalar curvature, \mathcal{L}_{SM} is the SM Lagrangian without the EBH field potential, and \mathcal{L}_N stands for the renormalizable (and scale invariant) extension of the SM by 3 sterile neutrinos N_I , L_α ($\alpha = 1, 2, 3$) being lepton doublets and $\tilde{H} = \epsilon H^*$, where ϵ is 2×2 antisymmetric matrix and H is the EBH doublet.

With potential (1) inflaton field X gets vacuum expectation value, which breaks scale invariance both in the sterile neutrino sector (making sterile and active neutrino massive via (3)) and in the SM sector (giving vacuum expectation v to the EBH field via mixing in the last term of (1)). Four parameters of the model, m_X , β , λ , and α , determine the EBH field vacuum expectation value $v \approx 246$ GeV, the Higgs boson mass $m_h \approx 126$ GeV [1, 2], and the inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}. \quad (4)$$

Thus, at a given value of β , the only free parameter in the scalar sector is the mixing coupling α or the inflaton mass m_χ . The particle spectrum in vacuum consists of the Higgs boson h and the inflaton χ of the mass m_χ , which are mixed (as compared to the $H - X$ basis) by a small mixing angle

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}. \quad (5)$$

Hence, the branching ratios of the inflaton decay into the SM particles (see [5] for details) are fixed for a given inflaton mass, see Figure 1.

At large field values potential (1) exhibits slow roll behavior along the direction $H^\dagger H = \alpha X^2/\lambda$, and supports the inflationary expansion of the early Universe. The non-minimal coupling to gravity (2) allows to control the amount of gravity waves generated at inflation [13] and for $\xi \gtrsim 10^{-3}$ is consistent [6] with the Planck bounds [14]. The tilt of the scalar perturbation power spectrum also agrees with cosmological data. For a given ξ the inflaton self-coupling β is determined from the amplitude of the primordial density perturbations [6].

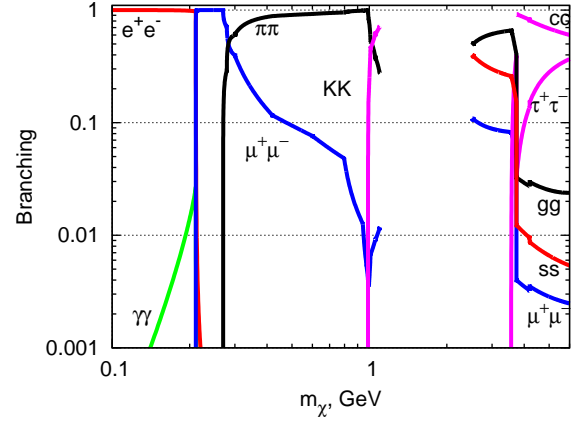


Figure 1: Inflaton decay branching rates [5] for two-body final states. In the mass region $m_\chi \simeq 1$ GeV predictions are highly uncertain because of the QCD effects.

To summarize, the model (1,2) has three new parameters ξ , β , and m_χ (or, equivalently, α), in addition to SM ¹, and they are determined from the following effects.

- β and ξ are related from the CMB normalization.
- m_χ and β are related by the requirement of the generation of proper abundance of DM (given DM mass M_1 or coupling f_1 is known).
- ξ can be determined from the measurement of the tensor-to-scalar ratio r of the primordial perturbations.

This in principle completely fixes all the parameters of the model. We treat m_χ as free parameter in this *Letter*, as far as the errors for the r determination are still quite large, and will discuss this further in the Conclusions.

At the same time the resulting values of the parameters should satisfy the set of constraints [5, 6]

- α is bound from below from the requirement of sufficient reheating,
- α is bound from above not to spoil the inflationary potential by radiative corrections,
- certain region in m_χ and θ (or, equivalently β) is constrained from particle physics experiments.

We show below that the first two are automatically satisfied with the parameters, leading to the proper DM generation, and the latter one leads to significant bound on the inflaton mass m_χ (and hence effective upper bound on r).

¹Parameter m_χ can be traded for the SM parameter v

2. Dark Matter generation

The lightest sterile neutrinos in (3) may serve as DM provided its tiny mixing to active neutrinos keeps it sufficiently long-lived. The dark matter particles may be produced in the primordial plasma via inflaton decays [3] due to Yukawa couplings in (3). They never come to equilibrium.

Let's discuss the production in details. The light inflaton is in thermal equilibrium down to rather small temperatures $T \ll m_\chi$, thanks to reactions $\chi \leftrightarrow e^+e^-, \mu^+\mu^-$, etc. Sterile neutrinos are produced in the inflaton decays mainly at $T \simeq m_\chi$, and their distribution function $n(p, t)$ (p is the neutrino 3-momentum and t is time) can be found from the solution of the kinetic equation

$$\frac{\partial n}{\partial t} - \mathcal{H}p \frac{\partial n}{\partial p} = \frac{2m_\chi \Gamma_{\chi \rightarrow N_1 N_1}}{p^2} \int_{p+m_\chi/4p}^{\infty} n_\chi(E) dE, \quad (6)$$

where the inverse decays $N_1 N_1 \rightarrow \chi$ are neglected, \mathcal{H} is the Hubble constant, E is the inflaton energy, $n_\chi(E)$ is the inflaton (thermal equilibrium) distribution, $\Gamma_{\chi \rightarrow N_1 N_1} = \beta M_1^2 / (8\pi m_\chi)$ is the partial inflaton width for the $\chi \rightarrow N_1 N_1$ decay.

One can obtain the analytic solution of (6) in the approximation of the time-independent effective number of degrees of freedom [3], but this approximation is not accurate enough for the interesting mass region $0.3 \text{ GeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$. Thus the numerical integration of (6) is required together with the input of the hadronic equation of state at GeV temperatures, which is not known exactly. For the estimate one can utilize the phenomenological equation of state from [15].

Such integration was performed in [3], and here we make use of these results. The relative contribution of sterile neutrino N_1 to the present Universe energy density Ω_N (must be 0.25 to fully explain DM) determines at given m_χ and M_1 the value of the quartic coupling β ,

$$\beta \simeq 1.4 \times 10^{-12} \times \left(\frac{S}{1.5 f(m_\chi)} \right) \left(\frac{m_\chi}{250 \text{ MeV}} \right)^3 \times \left(\frac{7 \text{ keV}}{M_1} \right)^3 \left(\frac{\Omega_N}{0.22} \right), \quad (7)$$

where $S \gtrsim 1$ is a dilution factor accounting for a possible entropy production due to late decay of the heavier sterile neutrinos $N_{2,3}$ [16] and the function $f(m_\chi)$ is determined by the effective number of degrees of freedom $g_*(T)$ in the primordial plasma at the inflaton decay. It changes monotonically from 0.9 to 0.4 for inflaton mass from 70 MeV to 500 MeV and for heavier inflaton can be approximated as $f(m_\chi) \simeq [10.75/g_*(m_\chi/3)]^{3/2}$ ($g_*(T)$ can be obtained from [15]). We further neglect possible dilution and possible contribution of other dark matter production mechanisms (e.g. neutrino oscillations amplified by lepton asymmetry in plasma [17]), which can increase or decrease β respectively. Then for a given beta one can readily reconstruct

the Higgs-inflaton mixing (5), see Figure 2, or the required value of non-minimal coupling ξ [6]. The mixing angle can be translated to the lifetime of the inflaton, see Figure 3.

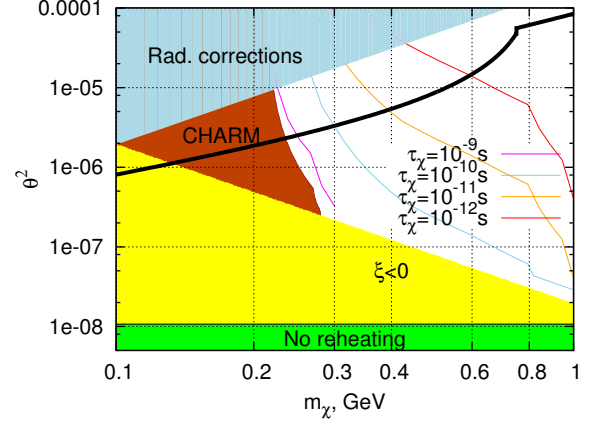


Figure 2: Higgs-inflaton squared mixing θ^2 (thick black line) depending on the light inflaton mass m_χ for the model with sterile neutrino dark matter of 7 keV mass. Various forbidden regions are shaded, and contours of the constant lifetime of the inflaton are shown. See [6] for details.

The moment mixing angle is known the rates of meson decays to the inflaton are determined. The most promising for the inflaton searches is the two-body decay of B-meson to kaon and inflaton, whose branching ratio is [5, 6]

$$\text{Br}(B \rightarrow \chi K) \simeq 4.8 \times 10^{-6} \times \left(1 - \frac{m_\chi^2}{m_b^2} \right)^2 \left(\frac{\theta^2}{10^{-6}} \right), \quad (8)$$

and is also presented in Figure 3 for the mixing θ^2 corresponding to the proper DM generation (Figure 2). Present accuracy in measurements of (limits on) three-body decays of B-meson into kaon and lepton pair, kaon and pion pair, kaon and kaon pair are at the level of $10^{-5} - 10^{-7}$ [18] and they are certainly relevant for short-lived inflaton, $\tau_\chi < 10^{-12} \text{ s}$.

One can also check, that the required Higgs-inflaton coupling $\alpha = \lambda \theta^2 / 2$ is within the bounds from reheating (which should happen in the early Universe before the electroweak sphaleron freeze-out, to allow for successful baryogenesis) and radiative corrections (not to spoil the inflaton potential) [4] for all interesting inflaton masses, see Figure 2.

The non-minimal coupling ξ determines uniquely the spectral index n_s and the tensor-to-scalar ratio r of the primordial perturbations. We give the cosmological predictions for the interesting inflaton mass range in Figure 4. Note that *measurement of the tensor modes r fixes the value of inflaton mass*.

Another important property is the momentum distribution of the generated DM neutrino. There are stringent bound on the free streaming length of a potentially Warm DM candidate from the analysis of the Lyman- α forest [19, 20]. While the exact reanalysis of the bounds

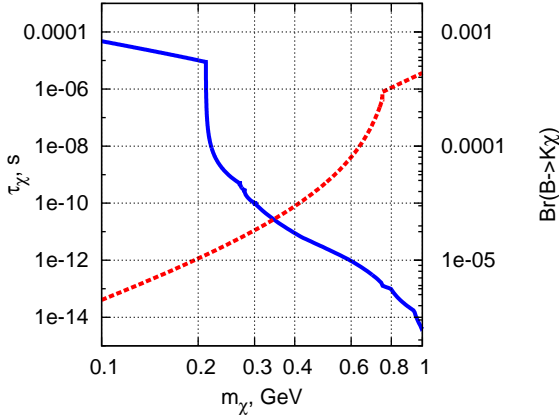


Figure 3: Inflaton lifetime (blue solid line, left vertical axis) and B-meson decay branching rate into inflaton and kaon (red dashed line, right vertical axis) as functions of the inflaton mass m_χ for the model with sterile neutrino DM of 7 keV mass.

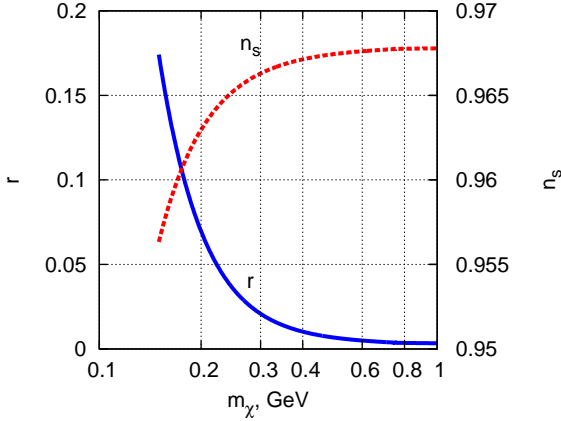


Figure 4: Predictions for the spectral index n_s (red dashed line, right vertical axis) and tensor-to-scalar ratio r (blue solid line, left vertical axis) of the primordial density perturbations depending on the inflaton mass (assuming $M_1 = 7$ keV DM production).

is complicated, as far as one should take into account the non-thermal shape of the spectrum, an estimate can be obtained by simple comparison of the average momentum of the generated DM neutrino. This is a good approximation, as far as in our case the spectral distribution does not have sharp resonant-like features. The average momentum of the neutrino is [3] (at temperatures T just above neutrino freeze-out)

$$\langle p \rangle \simeq 2.45 T \left(\frac{10.75}{g_*(m_\chi/3)} \right)^{1/3}, \quad (9)$$

which is below the usual thermal average of $p_T = 3.15 T$. One can then deduce the mass bounds from the analysis of structure formation. There are two types of bounds present in the literature: thermal relic bounds m_{TR} for the particles with the distribution of the thermal shape but lower temperature; and non-resonantly produced neu-

trino bound m_{NRP} , which has been obtained for $T = T_\nu$ and overall suppressed distribution. These bound can be translated to our case, which is intermediate (both average momentum is below thermal and overall distribution is suppressed), as

$$m_{Ly-\alpha}(\langle p \rangle) = \frac{\langle p \rangle}{p_T} m_{NRP} = \frac{\langle p \rangle}{p_T} m_{TR} \left(\frac{m_{TR}}{(\Omega_{DM} h^2) 94 \text{ eV}} \right)^{1/3}, \quad (10)$$

where $h \approx 0.7$. For the inflaton mass in the interesting range the corresponding lower limits on the fermion DM mass are outlined in Figure 5. The 7 keV DM is consistent with the first more conservative analysis [19] of Lyman- α forest data, but has tensions with the later analysis.

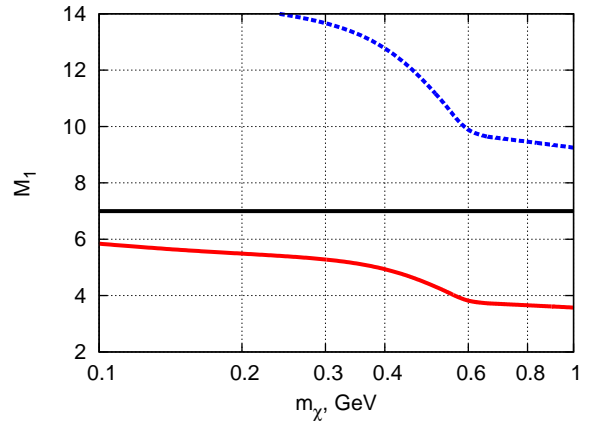


Figure 5: The Lyman- α lower bound on DM mass for DM produced by decays of the inflaton of mass m_χ . The lower and upper plots correspond to the bounds from [19] and [20], respectively. The 7 keV value is marked for reference.

3. Summary

In the model, where the non-minimally coupled inflaton serves as the only scale invariance breaking messenger for SM with three sterile neutrinos, sterile neutrino DM can be generated in the inflaton decays². In bosonic sector the model introduces three additional parameters—non-minimal coupling to gravity ξ , inflaton self coupling β , and the inflaton mass m_χ . The amplitude of the primordial perturbations relates first two of these parameters, ξ and β . Requirement of the proper abundance of the DM with a given mass M_1 provides the relation between the second pair, β and m_χ . Thus, assuming the mass of the DM is known, the only free parameter left is the inflaton mass. For numerical estimates we take $M_1 = 7$ keV, motivated by recent results [10, 11]. Further constraints on the model can be made from inflationary observations, specifically the tensor-to-scalar ratio r . Exact knowledge of r

²Two other sterile neutrinos giving masses to active neutrinos may be also adopted to explain baryon asymmetry of the Universe like in ν MSM [8].

would fix the value of ξ , and, thus, the inflaton mass m_χ leaving no free parameters (see Figure 4). Recent observation of $r \sim 0.1$ by BICEP2 [12] is consistent with our model and makes lower range of the inflaton mass preferable (higher values of r can even exclude the model, because low values of m_χ are excluded by particle physics experiments, especially CHARM [5, 21], see Figure 2).

The resulting low mass range is especially interesting, as far as for the inflaton masses of $230 \text{ MeV} \lesssim m_\chi \lesssim 600 \text{ MeV}$ the inflaton can be produced and searched in B-meson decays, see decay rate and inflaton lifetime in Figure 3. For the lower masses the lifetime of the inflaton is relatively long and the most interesting signature is the offset vertex of the inflaton decay into muon or pion pair after the B-meson decay vertex. For the higher masses the inflaton lifetime drops rapidly, and the possible signature is the peak in the B-meson three body decay kinematics. Note that the expected event rates are comparable with the current experimental sensitivity [6]. The lightest allowed inflatons may be searched for in beam-dump experiments (e.g. future CHARM successor SHIP at CERN).

Finally, we should note, that there are ways to slightly relax the relations for the model parameters. First is the possibility of the entropy generation in the decays of the heavier sterile neutrinos after the DM generation ($S > 1$). This allows for slightly larger β for given m_χ , leading to larger Higgs-inflaton mixing θ^2 , larger ξ , and smaller r . Additional generation of DM sterile neutrino N_1 after the inflaton decay (as in [9]) leads to the opposite effect. More significant deviations are possible if we allow for additional sources of the violations of the scale invariance. Specifically, allowing for arbitrary mass terms for the sterile neutrinos independent of the inflaton coupling would allow to relax all the relations for the DM generation. If 7 keV sterile neutrino is not the dominant component of DM, $\Omega_N < \Omega_{DM}$, Higgs-inflaton mixing θ^2 is smaller, hence larger r is allowed. It is worth to study thoroughly the consistency of the particular mechanism of DM production with observations of Ly- α forest, since present lower limits on the DM free-streaming [19, 20] fall in the right ballpark.

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